The ONUs can be designed to serve a great many subscribers, and collocated with existing telephone cabinets. Conversely, they can be made smaller, and placed at curb pedestals, or at the premises, where they become optical network terminals (ONTs). The ONU demultiplexes the subscriber signals and converts them into very-high-speed digital-subscriber-line (VDSL) format. These signals are transmitted to the subscriber premises using existing (or new) unshielded twisted pair (UTP) wiring and/or coaxial cable. It is important to note that the VDSL signal has rather short reach (1~5 kft) that depends on the delivered bandwidth.

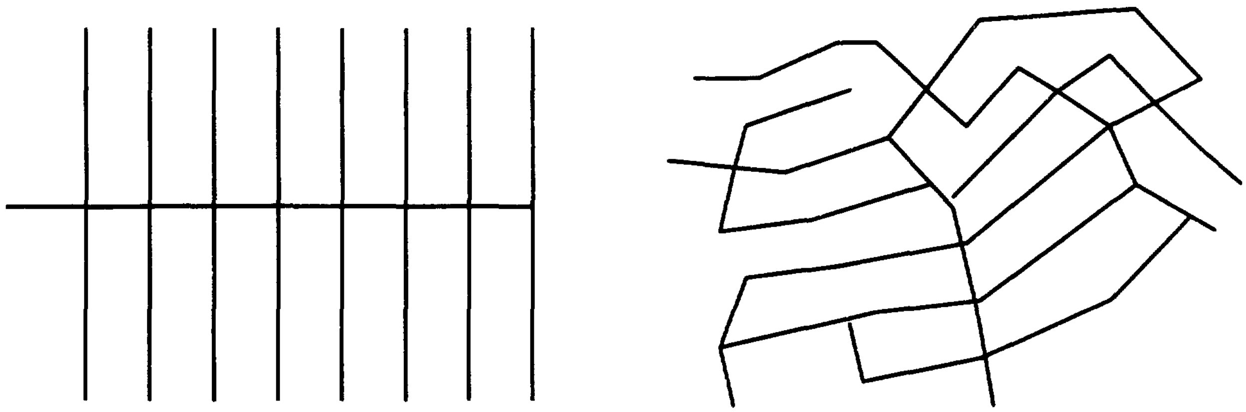
A key feature of these networks is the placement of shared network equipment such as optical network units (ONUs) in the outside plant. This sharing of equipment helps to reduce the total cost of such systems; however, these elements typically have limited capacity and range. These limitations can interact with the given distribution-area (DA) layout to reduce ONU utilization and increase cost. Recent work has revealed that ONU under-utilization can increase network cost significantly [4]. Hence, these effects are important to the design selection process, and must be modeled in order to optimize network cost.

For example, assume an ONU is constructed with capacity sufficient for serving 24 homes, and the VDSL links employed can span up to 1000 feet from the ONU to the home. Further assume that the ONU is placed on a street where the homes are spaced 250 feet apart. Based on the capacity of the ONU, one might expect that each ONU will be serving, on average, 24 homes. Due to the range limit, however, the ONU can only reach ~16 homes (eight on either side of the street). This is range-induced breakage, and in this example reduces the utilization of the ONUs to only 67%, resulting in an ONU cost 50% higher than that if range were not an issue.

Previously, fiber networks have been modeled by manually engineering a detailed design of the network based on a specific DA layout. The layout can be either created artificially using a simple grid-like model or taken from a real DA. A complete list of required components can be derived from the design. The list of components can then be combined with the component and installation costs to compute the installed first cost (IFC) of the network. It should be noted that the detailed design process produces far more information than that needed for the cost analysis, and this excess information represents a large inefficiency in the modeling method.

An example of artificial layouts shown in Fig. 2a consists of one main street with many identical side streets. The artificial layout is fairly simple to engineer, because the entire network design can be generated by replicating the relatively small side-street design. However, using artificial layouts can produce spurious results, such as sudden cost changes caused by relatively small changes in the design parameters. This stems from the lack of variability in the geography: because every street is identical, any change that occurs on one street is repeated on every street.

Using a real layout avoids this problem, but requires formidable engineering effort to process the complex layout. An example of real layouts shown in Fig. 2b exhibits the typical variation in street lengths and connections. It is obvious that the process of designing a fiber access network is a nontrivial problem with this kind of layout. Unless automated design tools are available, the design must be done manually, requiring many hours of engineering time.



(a) (b)

Fig. 2. Examples of (a) an artificial geographical layout, and (b) a realistic geographical layout.

2. Statistical Model

As explained above, the detailed design method for producing cost models of fiber access networks is not efficient in terms of engineering effort. We have developed a new model specifically designed to address this problem. The primary goal was to capture the complexity of real-world access networks while minimizing the amount of detailed network engineering. This has been accomplished by statistically modeling the DA as a collection of living units (LUs) placed at random locations in the layout. This allows the complex and highly arbitrary layout to be described by a few statistical parameters, such as LU density. The statistical model can then estimate the amount of equipment required to serve the DA without the lengthy network engineering process.

The basic concept behind the statistical method can be understood by considering the following example, diagrammed in Fig. 3. Here, we assume that we have a non-branched street with houses arranged randomly. The house placement can be described in several ways, including the distribution of house spacings, or the distribution of house number per length. For simplicity, we have chosen the distribution of house spacings to follow an exponential distribution, which implies the house placement is a Poisson process. The only parameter required is the average house density, given in homes per mile. This may seem unrealistic, as it ignores the semi-regular spacing that is typical for houses. However, the use of the Poisson process produces results that match those of actual network designs well. In addition, this method is general enough to allow other distributions to be used, if desired.

Given the street with houses, we must consider the equipment. Here, we assume that the ONU will be placed at the curb, and will have a certain subscriber capacity and range capability. The range distance used incorporates an allowance for the average length of the drop wires. In this example, we have chosen an ONU that can serve six subscribers, and has a range as shown. The ONUs are placed so that their coverage areas just touch each other, with as little over-capacity as possible. The number of homes within reach can then be computed using the Poisson distribution. In the case of ONU 1, there are not enough houses within reach of the ONU; hence, this ONU is under-utilized. In the case of ONU 2, there are too many homes within reach. In this case, the calculation involves reducing the ONU's coverage area until only six homes are served. The next zones contain four, six, and three homes, respectively. By integrating over all the possible cases, the total ONU density can be determined.

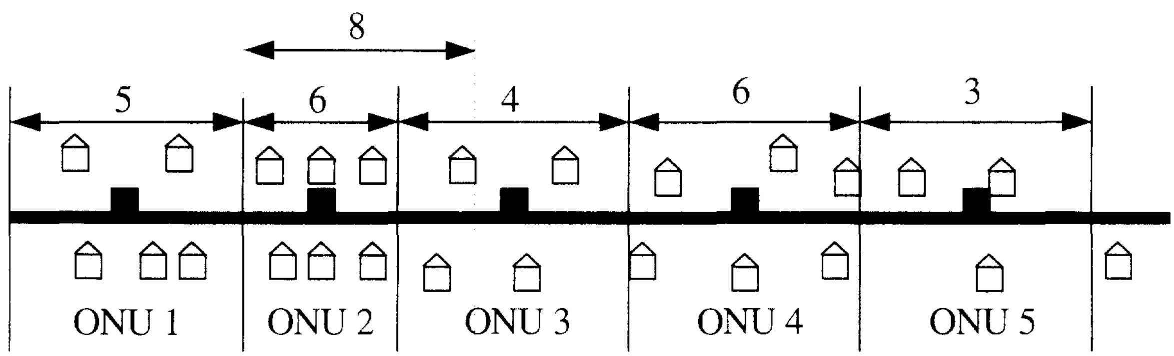


Fig. 3. An example of the statistical layout method. Here, a street without side streets is assumed to have houses distributed at random. The ONUs are placed to provide complete coverage subject to their range limitations.

This method is satisfactory when the ONU reach is short when compared with the typical length of the straight runs in the distribution plant being modeled. When the distribution plant branching length is shorter than the reach, then the situation begins to resemble that pictured in Fig. 4. Here, an ONU placed at the center of a grid-like distribution network can reach the homes it serves in two dimensions, as indicated by the diamond-shaped area. If we assume that the homes are distributed randomly over the area, and that the lots are, on average, square in aspect ratio, then we can compute the probability of having a certain number of homes within range. This probability can then be treated in the same way as before to compute the density of ONUs required to serve the area.

Of course, the non-branched street and the many-branched street are extreme cases. Any realistic setting would involve an intermediate solution, somewhere between the one-dimensional and two-dimensional cases. The mathematics of the distribution allows such a solution if we allow the dimension to assume real values between one and two. The choice of a dimension value would be another parameter to be determined by the user.

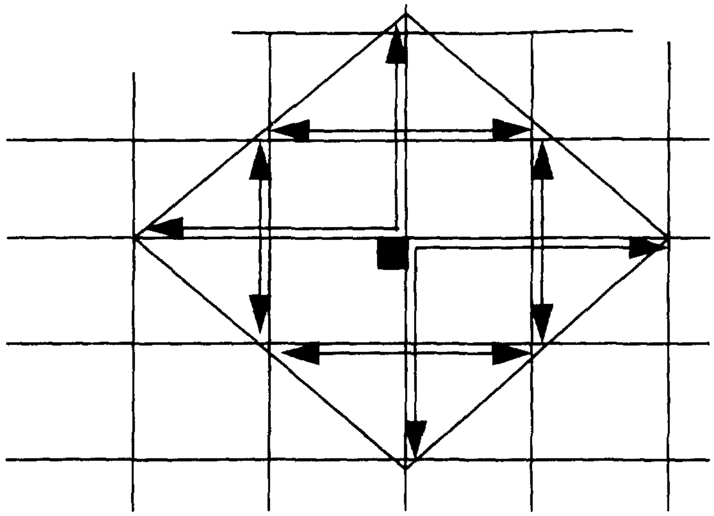


Fig. 4. An example where the distribution network forms a well-connected mesh. The ONU shown can reach homes in the two dimensional area shown.

This is a very simple example, and many more complications can be envisioned. For example, in many cases, an FTTx system will have two or three different ONU sizes. The model would then have to optimize the selection of the appropriate ONUs for each instance. There may be outside-plant rules, such as an ONU shall serve homes no more than one pole span away, or an ONU shall serve homes on only one side of the street. In any case, as long as the rule can be stated in terms of range and capacity constraints, it could be incorporated into the model. The basic power of the statistical approach is that it generates the distribution of servable clusters of homes without resorting to actual realizations of the geography.

3. Results

The results of our model compare closely with those obtained by the detailed design method. To obtain a set of results with which we could compare, an automated network design tool was used [5]. The network design tool performed detailed engineering on real geographic DA layouts describing typical suburban single-family neighborhoods with a nominal density of 66 homes per mile. The layouts were scaled linearly to simulate different densities. Two fiber-to-the-curb (FTTC) networks were modeled. One network had ONUs capable of serving 8 LUs, and the other had ONUs capable of serving 16 LUs.

The results of both the design tool and the statistical model are shown in Fig. 5. The design tool computed the ONU utilization at several values of LU density as shown by the data points, while the statistical model results are shown by the curves. There is very good agreement (RMS fractional cost error is 5%) between the actual design and the statistical model. Furthermore, this plot demonstrates the decrease in ONU utilization that occurs at low LU density, and the effect of ONU size.

It is important to note that while the design tool might take one minute to compute each data-point, the statistical model might take one minute to compute the entire curve (on the same machine). This illustrates the fact that the statistical model provides the answer at minimal computational cost, making it ideal for high-level design-selection purposes. Even more importantly, the statistical model does not require the voluminous map data as input, instead requiring, in this case, only two parameters, the density and the dimension.

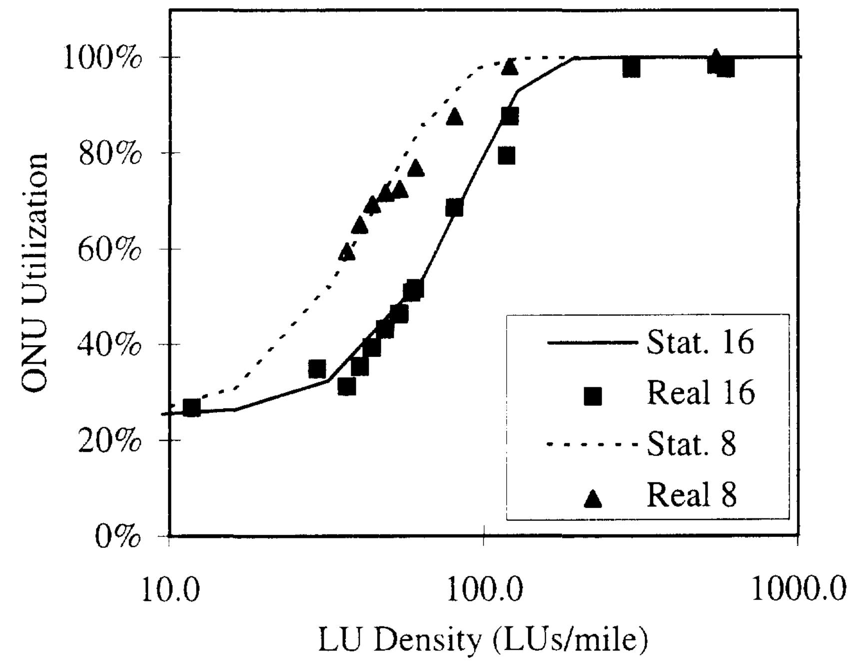


Fig. 5. The ONU utilization for FTTC networks with 8- and 16-LU ONUs computed by the statistical model and by a design algorithm operating on real layouts for a range of LU densities.

4. Software Implementation

While the statistical modeling method is useful, it does not solve the network cost-estimation problem completely. Therefore, we have developed a software tool that addresses this problem: the FTTx Selector. This program contains all the elements required to produce an accurate estimate of the network: problem description, network-element sizing, statistical network estimation, and report generation. It has an easy-to-use graphical user interface, and runs on IBM PC-compatible computers.

The first part of the problem is to define all the relevant inputs to the design problem. While this may seem to be an exercise in exposition, it is the foundation for any competent design. There are three major groups of inputs. The first group describes the geographical layout, and includes the housing density, the dimensions of the near and far distribution plant, the average DA size, etc. The second group describes the services to be provided, and includes their penetrations, bandwidths, and equipment requirements. The third group describes the equipment and facilities available, such as the number of ports on each type of line card, the bandwidth capability of an ONU, the sizes and costs of cable, etc. The FTTx Selector contains an editor that facilitates the definition of all these inputs, as well as the storage and retrieval of these inputs.

The second part of the problem is to determine the proper number of demand sources (living units) that each piece of equipment can serve. This process is commonly called sizing, and is essential to efficient design. The goal of sizing is the determination of the largest number of living units, N, that an element can serve while having a probability of exhaust less than a critical value. The FTTx Selector sizes equipment by searching over values of N, calculating the feasibility of serving N living units given their known rates of subscription to the various services (a straight-forward combinatorial problem).

The third part of the problem is to estimate the network; that is, to calculate the density of network elements and facilities, given in units per mile. Once this is determined, it is a little matter to determine the cost per mile, or most important, the cost per living unit. The FTTx Selector uses two statistical models, one to size the ONUs, linecards, and copper distribution cables, and the other to size the fiber plant, OLTs, and other CO-based equipment. The design estimation is complete with the derivation of all the element and facility densities.

The fourth and final part of the problem is to present meaningful reports with the data. The FTTx Selector provides flexibilities in how the inputs and outputs are handled. The output consists of a user-defined set of elements or groups of elements, and is given in terms of $/LU. The program also allows a whole sequence of estimations to be calculated at once by varying one or two input parameters over a user-defined range. This produces a one- or two-dimensional array of results. This feature is particularly useful to find prove-in points in the study of design alternatives. To facilitate the use of the results, they are placed into standard spreadsheet format, ready to be cut and pasted into standard processing packages.

5. Conclusions

This paper examined the general problem of access-network design estimation. The current method of analysis, detailed design, requires excessive design effort and user-defined input. We present a new method, statistical modeling, that can produce substantially the same result as the detailed design method, but with minimal design effort. This method uses the simplifying assumption that the houses are distributed at random in the area being served, and from this calculates the salient statistics required to estimate the needed equipment and facilities. This type of model can incorporate many different statistical assumptions and design rules, and can therefore find application in many situations. The results of the model were compared with results obtained by the detailed design method. The comparison revealed very close agreement (5 % RMS error), certainly good enough for high-level design selection.

A user-friendly implementation that incorporates this model has been developed, named the FTTx Selector. This application combines all the steps of network estimation: problem definition, equipment sizing, network cost estimation, and report generation. This application will be useful for both network providers who are looking to deploy the optimal FTTx network, and equipment suppliers who are looking to manufacture the best set of FTTx products.

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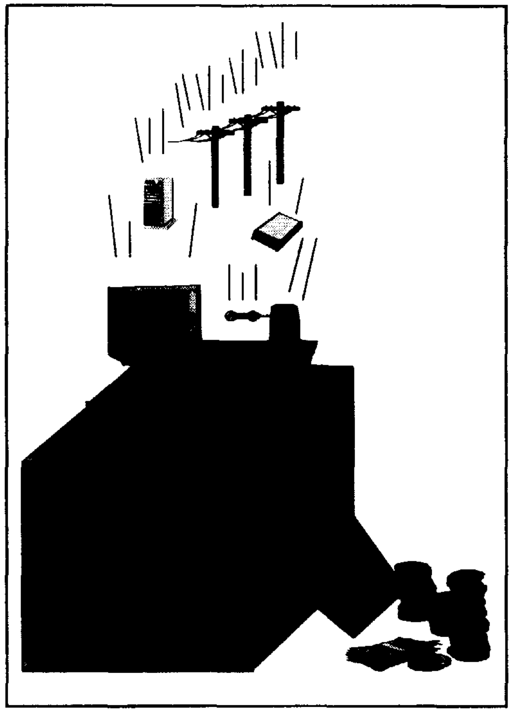
Modeling Access Networks Statistically – the FTTx Selector



Prepared For: NFOEC '97

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Sept. 24, 1997

Outline

- Motivation
- FSAN Architecture
- Statistical Approach
- Results
- FTTx Selector Tool
- Conclusions

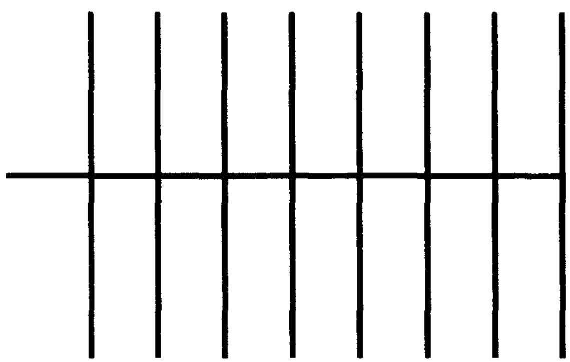
Motivation

- Selecting the best architecture
- Interested parties
  - Equipment vendors
  - Network providers
  - Analyst consultants
- Current analysis is labor intensive
  - Network engineering
  - Spreadsheet maintenance

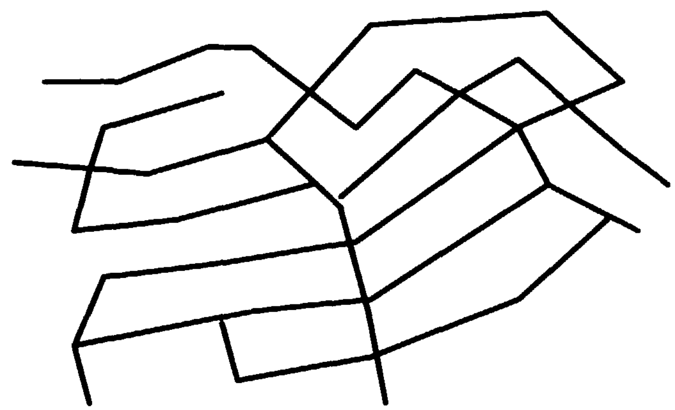
Network Engineering

- Design rules
  - Capacity engineering
  - Range limitations
- Geographical layout

Grid
- Easier to design
- Less realistic



Actual Map
- More realistic
- Harder to design



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Spreadsheet Maintenance

	Analytical	Historical
• Design rules -	designer	existing system
• Outside plant layout -	engineer	experience
• Define costs -	analyst	market

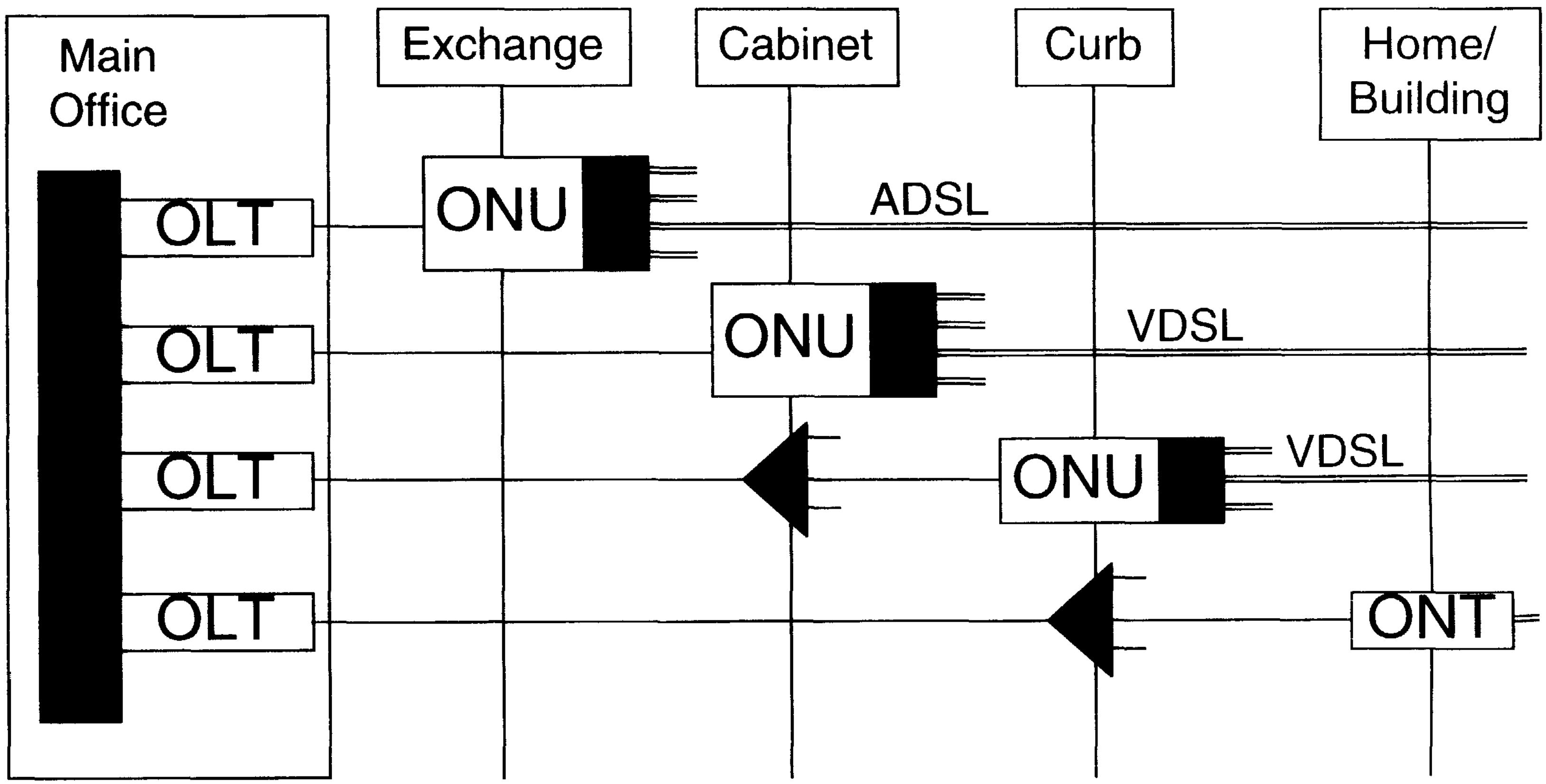
- Integrate with spreadsheet
  - Hard to revise / features often 'hard-wired'
  - Prone to error / difficult to error check
  - No standard format / difficult to compare results
- Bottom line:

  Every analysis requires repeated, multiperson effort
  Automation would improve accuracy and reduce cost

A Need To Focus: FTTx

- The biggest problem with tools
  - A general tool is very difficult to achieve (at first)
  - A specific tool is not very useful
- Fiber-to-the-x (Exchange, Cabinet, Curb, Home)
  - Has gathering acceptance among network providers (Gx)
  - Is a specific network that has many variations
  - Presents interesting and non-obvious analysis problems
  - Currently in development stage
- A tool to analyze all FTTx variations:
  The FTTx Selector

FTTx Architecture



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FSAN Issues

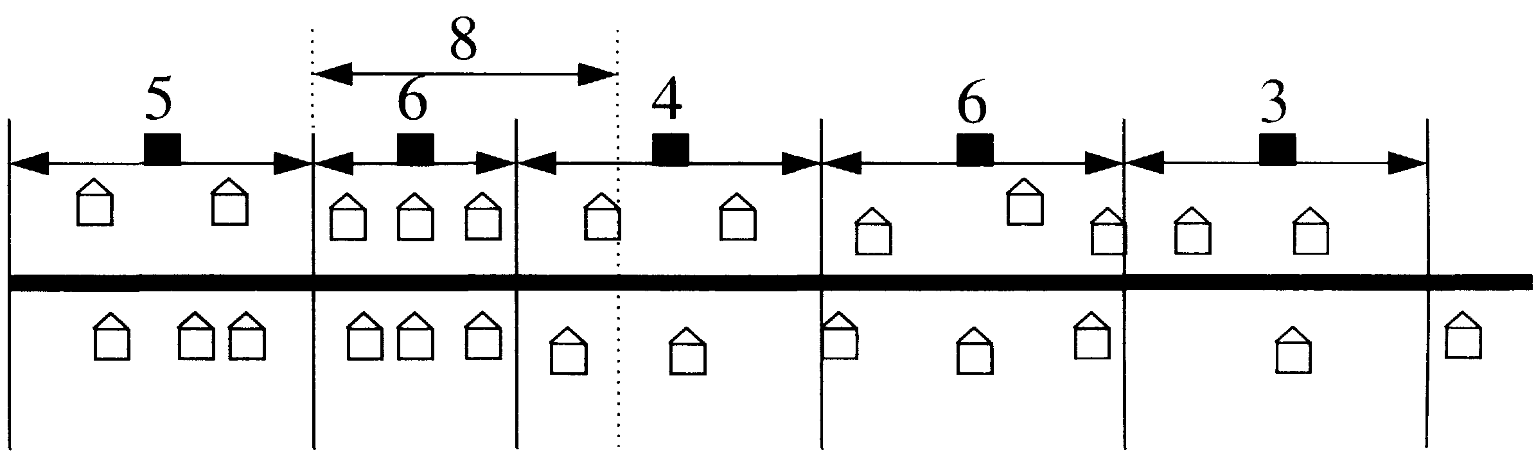
- Which version is best in what setting?
  - ONU size
  - Subscriber density
  - VDSL line rate / reach
- How to handle lower penetration?
  - ONU and OLT capacity engineering
  - Outside plant configuration

Statistical Approach

- Goals
  - Model real world geography and breakage
  - Require minimal user inputs and intervention
  - Be efficient and easy to implement
- Assumptions
  - Houses are distributed randomly with density, **d**
  - ONUs with reach, **r**, are placed for contiguous coverage
  - Placement is optimized for minimum cost

One-Dimensional Street

- ONUs assumed to be regularly spaced
- The number of homes in each zone is Poisson-distributed with parameter **2 r d**
- High-occupancy zones are subdivided



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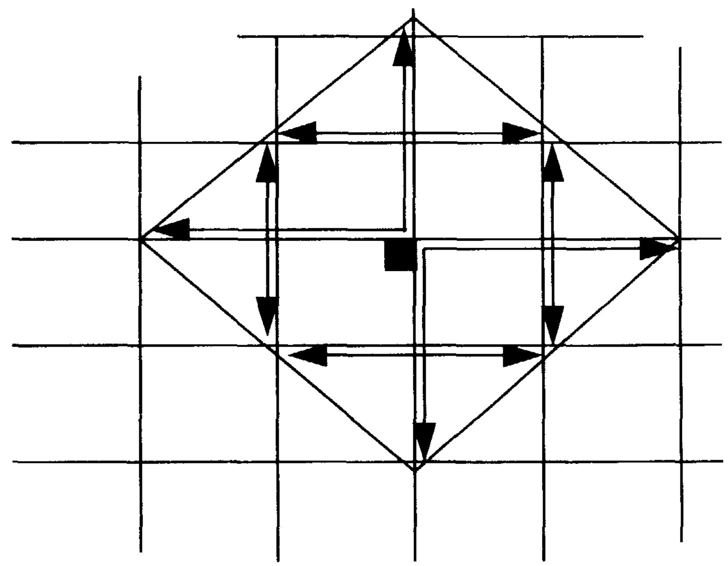
Life Is Not a One-Way Street

- When streets form a branched network, ONU can reach homes in two dimensions
- Number of homes in zone is still Poisson-distributed, with parameter $\mathbf{2 (r d)^2}$
- Generalized parameter

  $\mathbf{2 (r d)^n}$,

  where **n** is dimension

  in [1,2]



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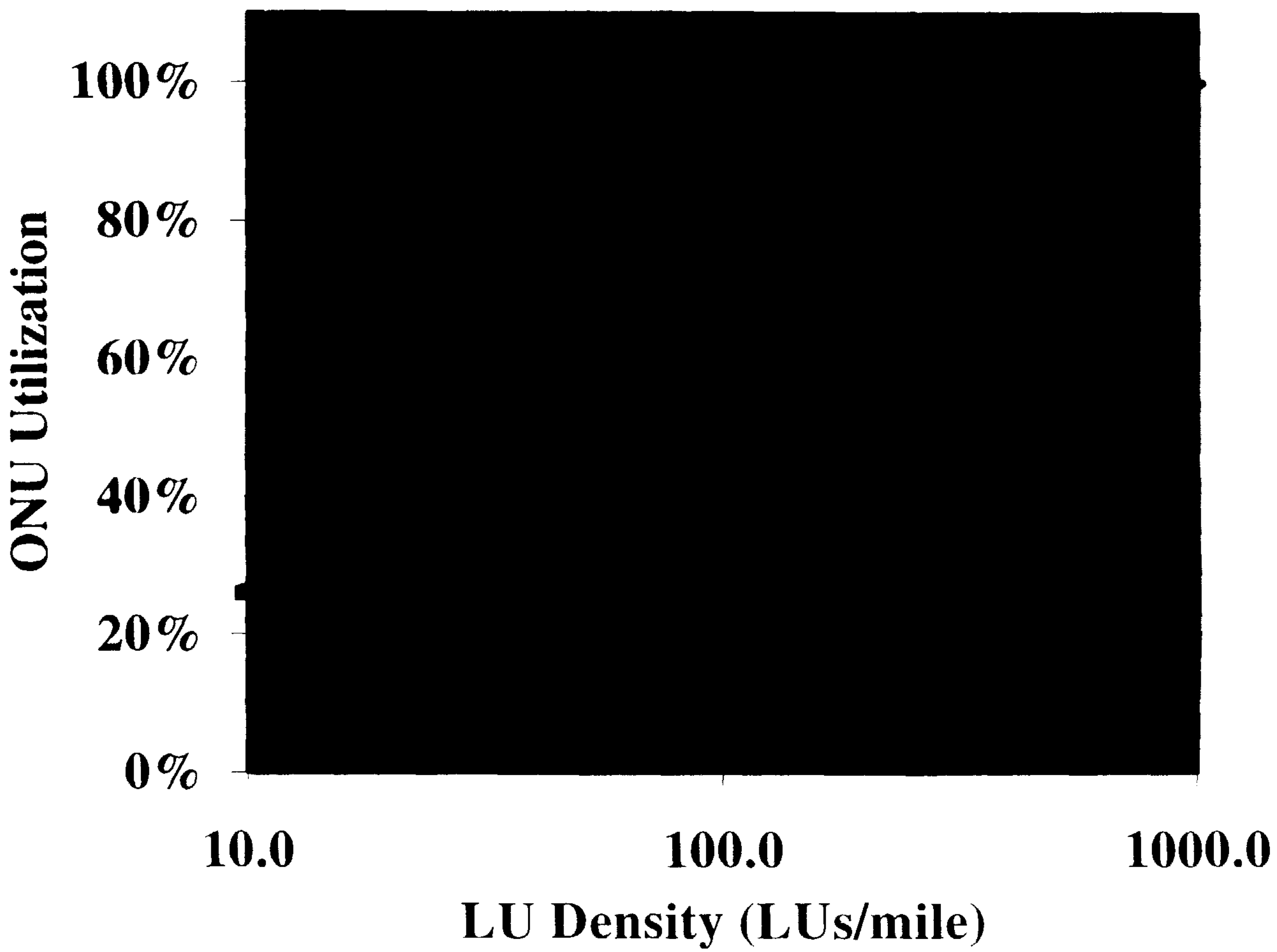
Results

- Compare results to actual design
  - Based on real suburban layout
  - Layout was scaled to vary density
  - Various ONU sizes were used
- ONU utilization factor
  - Clearly defined (LU served / LU capacity)
  - Doesn't involve costs
  - Most important breakage effect

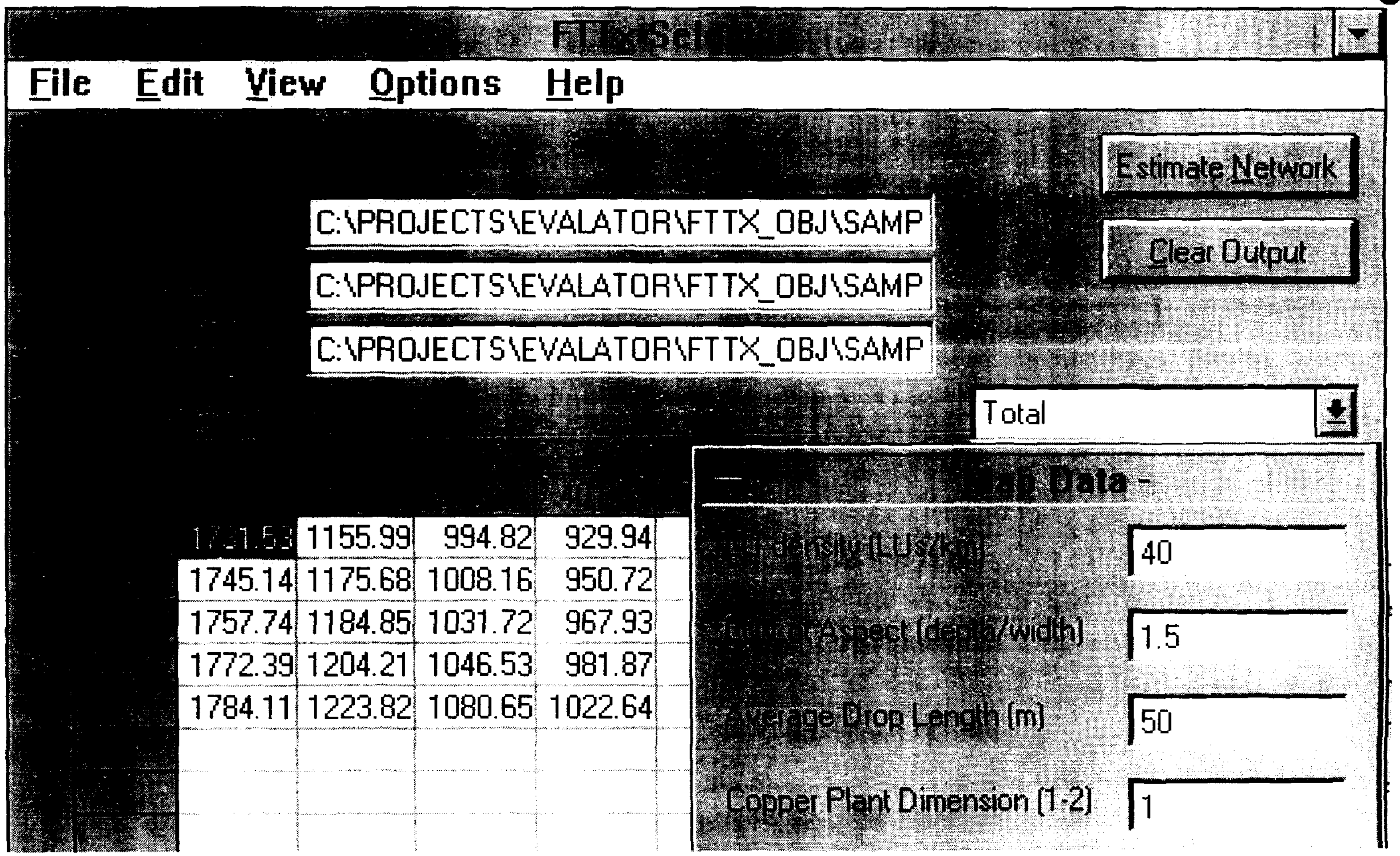
ONU Utilization



FTTx Selector

- Full automation of selection process
  - FTTx architecture is well defined
  - Engineering rules parameterized
  - Capacity engineering model
  - Statistical geographical model
- All models integrated into application
  - Standardized inputs
  - Standardized analysis
  - Standardized outputs
  - Graphical interface

FTTx Selector User Interface



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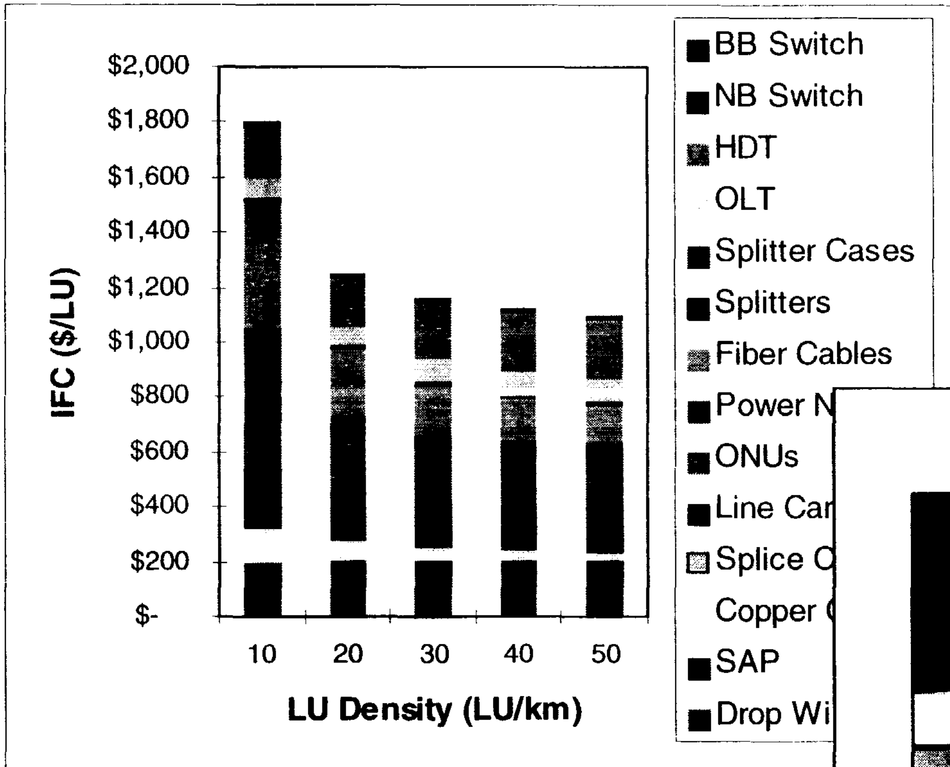
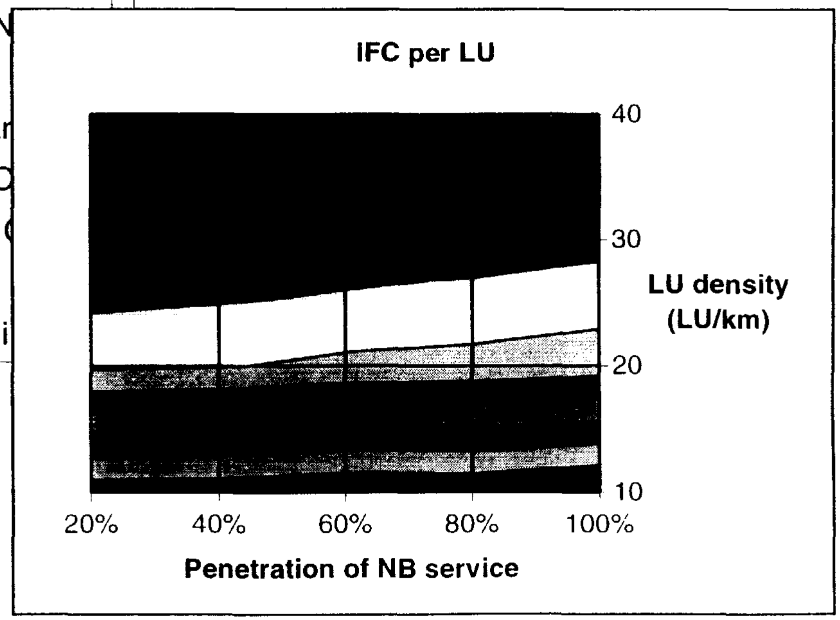
FTTx Selector Sample Output





Example calculations for Full Service FTTC, ONU serving ~15 LU

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Conclusions

- Need for architecture selection tool
- FTTx architecture is important focus
- Statistical models balance simplicity and accuracy
- FTTx Selector tool handles all design problems
- Available for consulting and third-party use

A New Approach to Network Planning and Engineering

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ABSTRACT

This paper presents an approach to access network planning and engineering that can incorporate a large number of alternative technologies and architectures and can be upgraded to accommodate new distribution technologies and architectures as they are developed. This approach can study arbitrary combinations of POTS, data broadcast video, one-way switched video, and two-way switched video services. In addition, the approach can be used to model and study any geographic area, ranging from real-world areas to idealized rectangular grid-type layouts. The approach has been implemented in the *Optiaccess*™ software system at Bellcore.

INTRODUCTION

Software systems that evaluate alternative local access network designs are an important tool for planning and engineering networks. These systems enable local access providers to compare alternative networks in terms of cost and other criteria, to evaluate the business risks and trade-offs among deployment possibilities, and ultimately to determine where and how to build new networks. Designers and manufacturers of local access network equipment can also use planning and engineering tools to analyze the network impacts of alternative equipment designs and to demonstrate the value of one equipment design over another. These uses of planning and engineering systems are summarized in Fig. 1.

Planning and engineering systems for copper networks have been developed over a period of many years and ate relatively mature. The proliferation of numerous emerging local access technologies and ways of configuring those technologies, however, require capabilities beyond those of current systems. This suggests the need for anew generation of planning and engineering tools.

Some of the capabilities needed in new planning and engineering systems aresummarized in Fig. 2. These tools should be able to examine today's emerging network architectures, including many varieties of fiber-coax, fiber-to-the-curb, and fiber-to-the-home architectures. It should also be possible to modify them to accommodate future architectures, possibly based on radically different technologies than those available or even imagined currently. New tools should also take account of variations in offered services and traffic demands from one area to another and changes in component costs over time.

Figure 3 lists some of the key parameters of which new planning and engineering systems must be able to take account, Some of these are important parameters for copper network planning and engineering also, such as population density, topology, and revenues. Others, however, are new for the next generation of tools. These include bit rates and bandwidths of new servies, blocking probabilities that may vary from one service to another, and a large number of technical characteristics, such as attenuation of coaxial cable at different frequencies, splitting ratios, and tap losses. The next generation of planning and engineering systems must take account of these new parameters by enabling users to set values for them where appropriate and by incorporating them into the network design and evaluation process.

Optiaccess is a trademark of Bellcore.

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